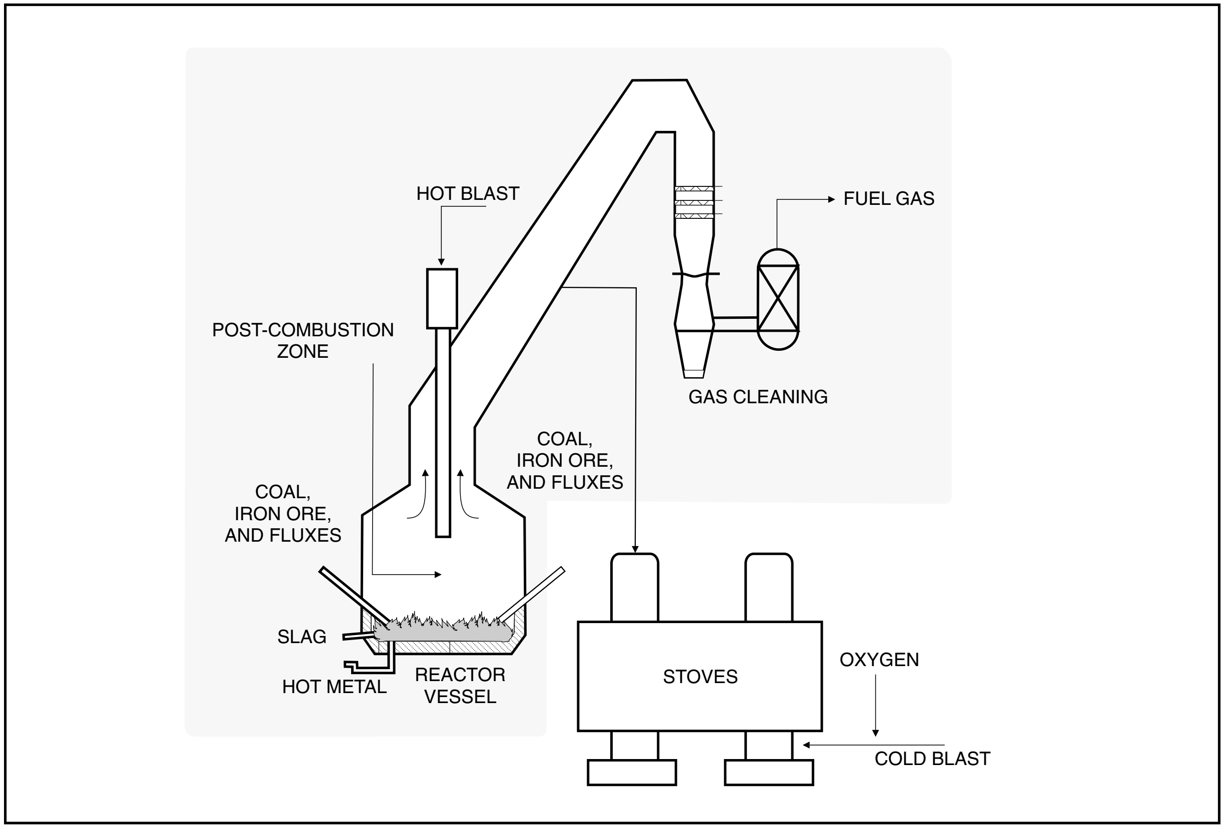
# Industrial Applications

# Clean Power from Integrated Coal/Ore Reduction (CPICOR™)




### Participant

CPICOR™ Management Company L.L.C. (a limited liability company composed of subsidiaries of the Geneva Steel Company)

### Additional Team Members

Geneva Steel Company—cofunder, constructor, host, and operator of unit

### Location

Vineyard, Utah County, UT (Geneva Steel Co.'s mill)

### Technology

HIsmelt® direct iron making process

### Plant Capacity/Production

3,300 tons/day liquid iron production

### Coal

Bituminous, 0.5% sulfur

### Project Funding

| | | |
|---|---|---|
| Total project cost | $1,065,805,000 | 100% |
| DOE | 149,469,242 | 14 |
| Participant | 916,335,758 | 86 |

### Project Objective

To demonstrate the integration of direct iron making with the coproduction of electricity using various U.S. coals in an efficient and environmentally responsible manner.

### Technology/Project Description

The HIsmelt® process is based on producing hot metal and slag from iron ore fines and non-coking coals. The heart of the process is producing sufficient heat and maintaining high heat transfer efficiency in the post-combustion zone above the reaction zone, to reduce and smelt iron oxides. Tests have demonstrated 60% post-combustion levels (degree of post-combustion attained) with 90% heat transfer efficiency.

The HIsmelt® process uses a vertical smelt reduction reactor, which is a closed molten bath vessel, into which iron ore fines, coal, and fluxes are injected. The coal is injected into the bath where carbon is dissolved rapidly. The carbon reacts with oxygen (from the iron ore) to form CO and metallic iron. Injection gases and evolved CO entrain and propel droplets of slag and molten iron upward into the post-combustion zone.

The iron reduction reaction in the molten bath is endothermic; therefore, additional heat is needed to sustain the process and maintain hot metal temperature. This heat is generated by post-combusting the CO and hydrogen from the bath with an $O_2$-enriched hot air blast from the central top lance. The heat is absorbed by the slag and molton iron droplets and returned to the bath by gravity. Droplets in contact with the gas in the post-combustion zone absorb heat, but are shrouded during the descent by ascending reducing gases (CO), which, together with bath carbon, prevent unacceptable levels of FeO in the slag.

The molten iron collects in the bottom of the bath and is continuously tapped from the reactor through a fore-hearth, which maintains a constant level of iron in the reactor. Slag, which is periodically tapped through a conventional blast furnace-type tap hole, is used to coat and control the internal cooling system and reduce the heat loss.

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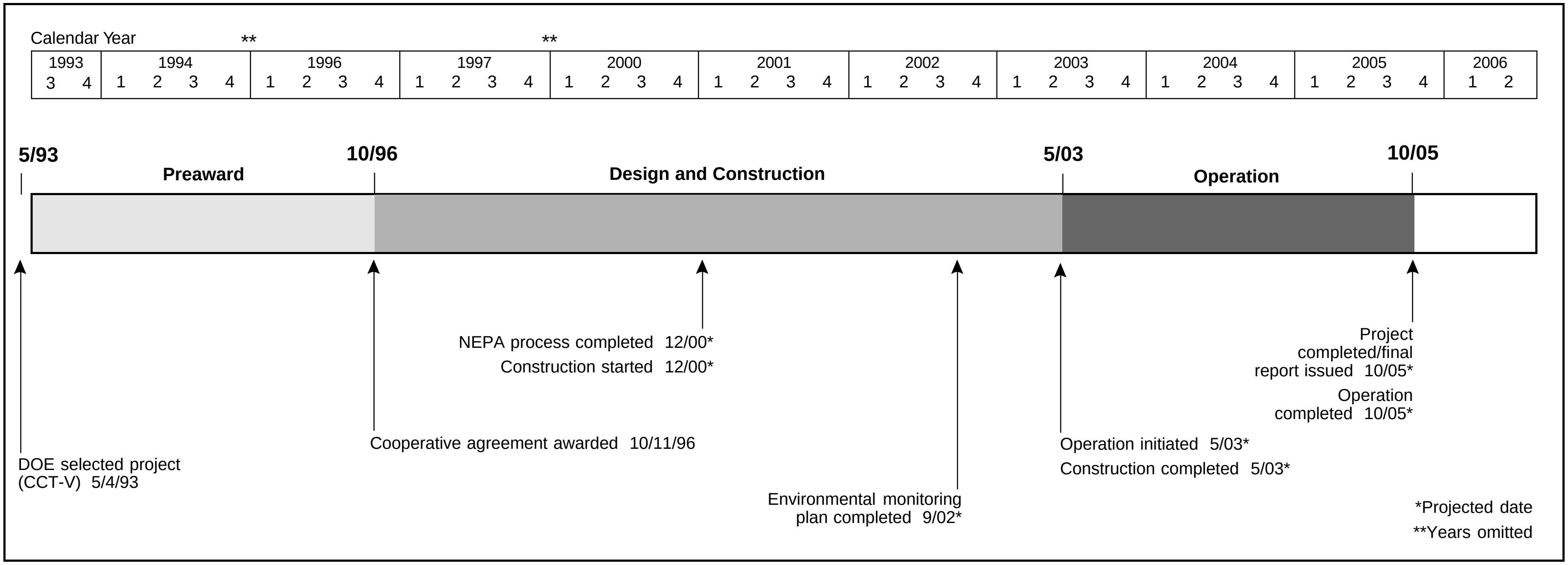
HIsmelt is a registered trademark of HIsmelt Corporation Pty Limited.
CPICOR is a trademark of the CPICOR™ Management Company, L.L.C.




Reacted gases, mainly $N_2$, $CO_2$, CO, $H_2$, and $H_2O$, exit the vessel. After scrubbing the reacted gases, the cleaned gases will be combusted to produce 170 MWe of power. The cleaned gases can also be used to pre-heat and partially reduce the incoming iron ore.

## Project Status/Accomplishments

The cooperative agreement was awarded on October 11, 1996. CPICOR™ analyzed the global assortment of new direct ironmaking technologies to determine which technology would be most adaptable to western U.S. coals and raw materials. Originally, the COREX® process appeared suitable for using Geneva's local raw materials; however, lack of COREX® plant data on 100% raw coals and ores prevented its application in this demonstration. Thus, CPICOR™ chose to examine alternatives. The processes evaluated included: AISI direct ironmaking, DIOS, Romelt, Tecnored, Cyclonic Smelter, and HIsmelt®. The HIsmelt® process appears to offer good economic and operational potential, as well as the prospect of rapid commercialization. CPICOR™ has completed testing of two U.S. coals at the HIsmelt® pilot plant near Perth, Australia.

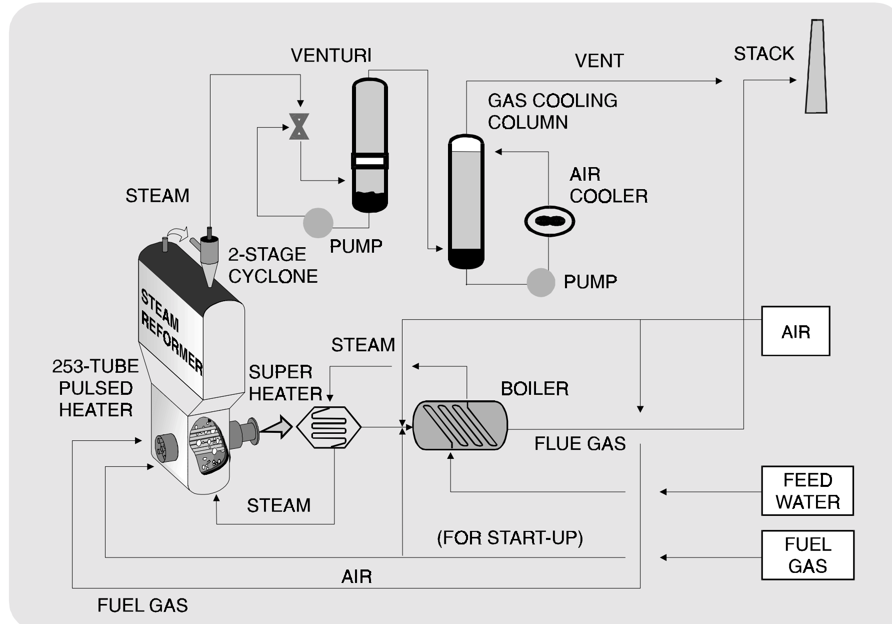
On February 1, 1999, Geneva Steel Company (CPICOR™ Management Company's parent corporation) filed a voluntary petition for bankruptcy under Chapter 11 of the United States Bankruptcy Code in the U.S. Bankruptcy Court for the District of Utah. Geneva Steel intends to emerge from Chapter 11 with a restructured balance sheet that will enable full participation in this demonstration project. Other developments include the following: DOE is reviewing final drafts of license and marketing agreements between HIsmelt® and CPICOR™; DOE has established a NEPA Team to review the Environmental Information Volume and begin the NEPA scoping process; and baseline air monitoring is in progress.

## Commercial Applications

The HIsmelt® technology is a direct replacement for existing blast furnace and coke-making facilities with additional potential to produce steam for power production. Of the existing 79 coke oven batteries, half are 30 years of age or older and are due for replacement or major rebuilds. There are about 60 U.S. blast furnaces, all of which have been operating for more than 10 years, with some originally installed up to 90 years ago. HIsmelt® represents a viable option as a substitute for conventional iron making technology.

The HIsmelt® process is ready for demonstration. Two pilot plants have been built, one in Germany in 1984 and one in Kwinana, Western Australia in 1991. Through test work in Australia, the process has been proven—operational control parameters have been identified and complete computer models have been successfully developed and proven. The goal is to have a fully operational commercial plant by early next decade.

# Pulse Combustor Design Qualification Test




### Participant
ThermoChem, Inc.

### Additional Team Member
Manufacturing and Technology Conversion International, Inc. (MTCI)—technology supplier

### Location
Baltimore, MD (MTCI Test Facility)

### Technology
MTCI's Pulsed Enhanced™ Steam Reforming using a multiple resonance tube pulse combustor.

### Plant Capacity/Production
30 million Btu/hr (steam reformer)

### Coal
Black Thunder (Powder River Basin) subbituminous

### Project Funding

| | | |
|---|---|---|
| Total project cost | $8,612,054 | 100% |
| DOE | 4,306,027 | 50 |
| Participants | 4,306,027 | 50 |

### Project Objective
To demonstrate the operational/commercial viability of a single 253-resonance-tube pulse combustor unit and evaluate characteristics of coal-derived fuel gas generated by an existing Process Development Unit (PDU).

### Technology/Project Description
MTCI's Pulsed Enhanced™ Steam Reforming process incorporates an indirect heating process for thermochemical steam gasification of coal to produce hydrogen-rich, clean, medium-Btu content fuel gas without the need for an oxygen plant. Indirect heat transfer is provided by immersing multiple resonance-tube pulse combustors in a fluidized-bed steam gasification reactor. Pulse combustion increases the heat transfer rate by a factor of 3 to 5, thus greatly reducing the heat transfer area required in the gasifier.

The pulse combustor represents the core of the PulsedEnhanced™ Steam Reforming process because it provides a highly efficient and cost-effective heat source. Demonstration of the combustor at the 253-resonance-tube commercial-scale is critical to market entry. The 253-resonance-tube unit represents a 3.5 scale-up from previous tests. Testing will seek to verify scale-up criteria and appropriateness of controls and instrumentation. Also, an existing PDU will be used to gasify coal feedstock to provide fuel gas data, including energy content, species concentration, and yield. Char from the PDU will be evaluated as well.

The facility will also have a product gas cleanup train that includes two stages of cyclones, a venturi scrubber with a scrubber tank, and a gas quench column. An air-cooled heat exchanger will be used to reject heat from the condensation of excess steam (unreacted fluidization steam) quenched in the venturi scrubber and gas quench column. All project testing will be performed at the MTCI test facility in Baltimore, Maryland.

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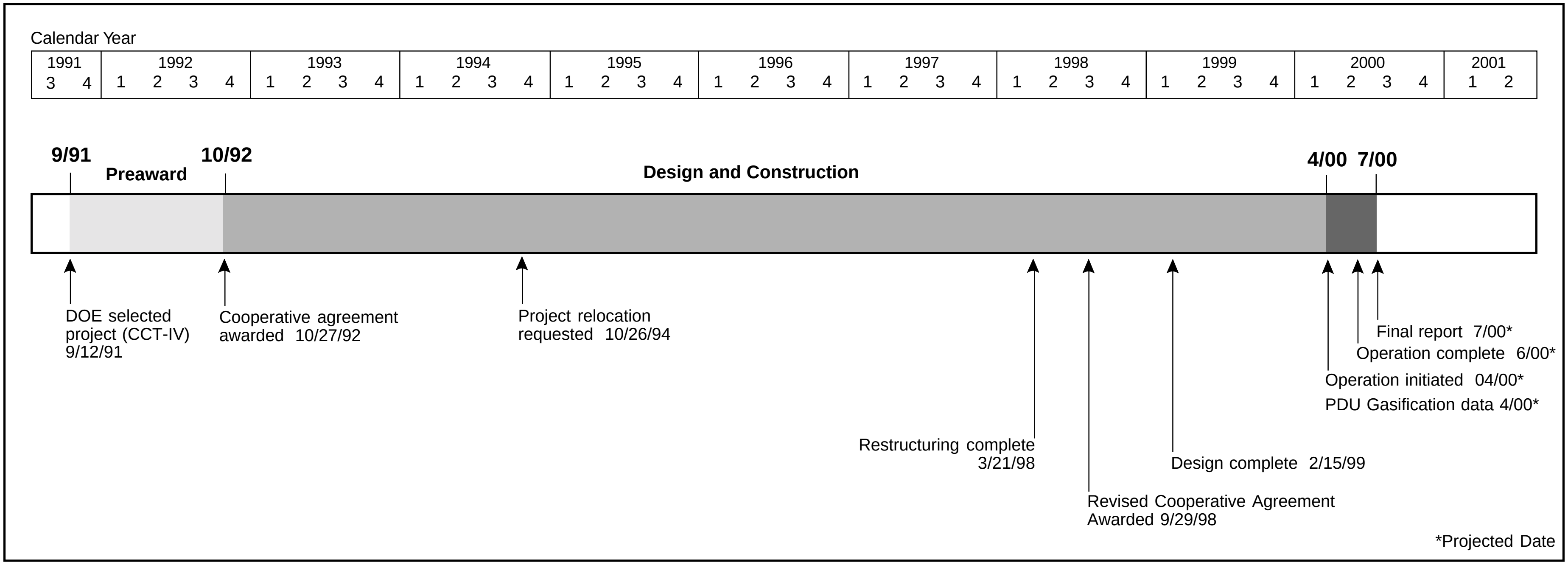
PulseEnhanced is a trademark of MTCI.




## Project Status/Accomplishments

On September 10, 1998, DOE approved revision of ThermoChem, Inc.'s Cooperative Agreement for a scaled-down project. The original project, awarded in October 1992, was a commercial demonstration facility that would employ 10 identical 253-resonance-tube pulse combustor units. After fabrication of the first combustor unit, the project went through restructuring. The revised project will demonstrate a single 253-resonance-tube pulse combustor. NEPA requirements were satisfied on November 30, 1998, with a Categorical Exclusion. The first major milestone was completion of the design on February 15, 1999.

Construction of the combustor unit is scheduled to be completed in March 2000, with operations beginning in April 2000. The mild coal gasification data will be collected in April 2000 using the existing PDU.

## Commercial Applications

PulsedEnhanced™ Steam Reforming has application in many different processes. Coal, with the world production on the order of four billion tons per year, constitutes the largest potential feedstock for steam reforming. Other potential feedstocks include spent liquor from pulp and paper mills, refuse-derived fuel, municipal solid waste, sewage sludge, biomass, and other wastes.

Although the project will demonstrate mild gasification only, the following coal-based applications are envisioned:

- Coal processing for combined-cycle power generation,
- Coal processing for fuel cell power generation,
- Coal pond waste and coal rejects processing to produce a hydrogen-rich gas from the steam reformer for use in overfiring or reburning to reduce $NO_x$ emissions,
- Coal processing for production of gas or liquid fuel, and char for the steel industry for use in direct reduction of iron ore,
- Coal processing for producing compliance fuels,
- Mild gasification of coal,
- Co-processing of coal and wastes, and
- Coal drying.

In addition, the technology has application for black liquor processing and chemical recovery and for hazardous, low-level radioactive, and low-level mixed waste volume reduction and destruction.

# Blast Furnace Granular-Coal Injection System Demonstration Project

***Project completed.***

### Participant
Bethlehem Steel Corporation

### Additional Team Members
British Steel Consultants Overseas Services, Inc. (marketing arm of British Steel Corporation)—technology owner
CPC-Macawber, Ltd. (formerly named Simon-Macawber, Ltd.)—equipment supplier
Fluor Daniel, Inc.—architect and engineer
ATSI, Inc.—injection equipment engineer (North America technology licensee)

### Location
Burns Harbor, Porter County, IN (Bethlehem Steel's Burns Harbor Plant, Blast Furnace Units C and D)

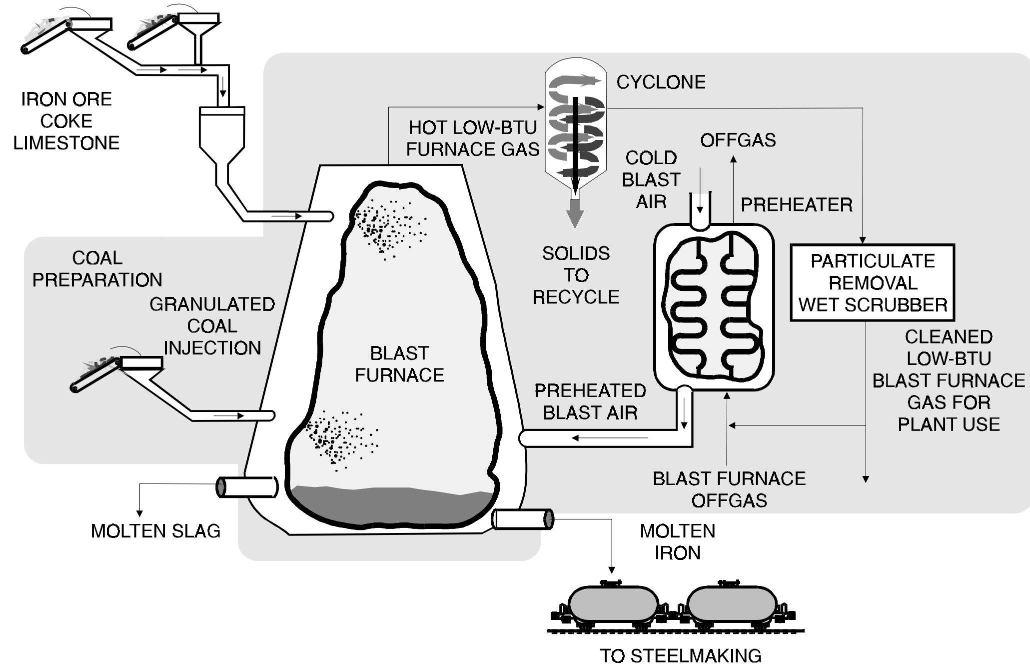
### Technology
British Steel and CPC-Macawber blast furnace granular-coal injection (BFGCI) process

### Plant Capacity/Production
7,000 net tons of hot metal (NTHM)/day (each blast furnace)

### Coal
Eastern bituminous, 0.8–2.8% sulfur
Western subbituminous, 0.4–0.9% sulfur

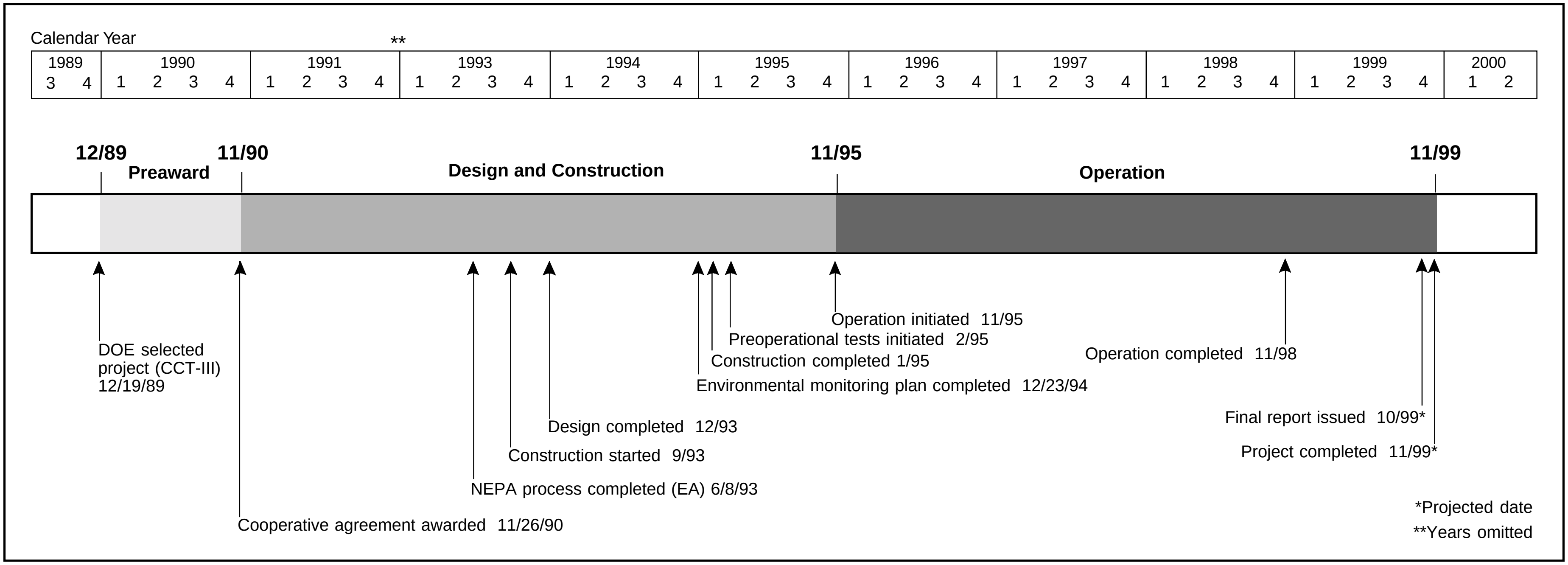
### Project Funding

| | | |
|---|---|---|
| Total project cost | $194,301,790 | 100% |
| DOE | 31,824,118 | 16 |
| Participant | 162,477,672 | 84 |




### Project Objective
To demonstrate that existing iron making blast furnaces can be retrofitted with blast furnace granular-coal injection technology; to demonstrate sustained operation with a variety of coal types, particle sizes, and injection rates; and to assess the interactive nature of these parameters.

### Technology/Project Description
In the BFGCI process, either granular or pulverized coal is injected into the blast furnace in place of natural gas or oil as a blast furnace fuel supplement. The coal, along with heated air, is blown into the barrel-shaped section in the lower part of the blast furnace through passages called tuyeres, which creates swept zones in the furnace called raceways. The size of a raceway is important and is dependent upon many factors, including temperature. Lowering of a raceway temperature, which can occur with natural gas injection, reduces blast furnace production rates. Coal, with a lower hydrogen content than either natural gas or oil, does not cause as severe a reduction in raceway temperatures. In addition to displacing natural gas, the coal injected through the tuyeres displaces coke, the primary blast furnace fuel and reductant (reducing agent), on approximately a pound-for-pound basis up to 40% of total requirements. Emissions generated by the blast furnace itself remain virtually unchanged by the injected coal; the gas exiting the blast furnace is cleaned and used in the mill. Sulfur from the coal is removed by the limestone flux and bound up in the slag, which is a salable by-product. Two high-capacity blast furnaces, Units C and D at Bethlehem Steel's Burns Harbor Plant, were retrofitted with BFGCI technology. Each unit has a production capacity of 7,200 NTHM/day. The two units use about 2,800 tons/day of coal during full load operation.




## Results Summary

### Environmental

- The BFGCI technology has the potential to reduce pollutant emissions substantially by displacing coke, the production of which results in significant emissions of air toxics.

### Operational

- The low-ash, low-volatile, high-carbon coal provided a high coke replacement value.
- Reliability of the coal system enabled the operators to reduce furnace coke to a low rate of 661 lb/NTHM (pre-demonstration rate was 740 lb/NTHM).
- During the base period, permeability of the carbon layer in the blast furnace burden column (a critical parameter) indicated overall acceptable operation using low-ash, low-volatile, high-carbon coal.
- Granular coals are easier to handle in pneumatic conveying systems than pulverized coal because granular coals are not as likely to stick to conveying pipes if moisture control is not adequately maintained.
- Any decrease in furnace permeability as a result of coal injection can be minimized by increasing oxygen enrichment and raising moisture additions to the blast furnace.
- Higher ash coal had no adverse effect on furnace permeability.
- The productivity rate of the furnace was not affected by the 2.4 percentage point increase in coal ash at an injection rate of 260 lb/NTHM.
- There is a coke rate disadvantage of 3 lb/NTHM for each 1 percentage point increase of ash in the coal at an injection rate of 260 lb/NTHM.
- Hot metal quality was not affected by the increased ash content of the injection coal.

### Economic

- The capital cost for one complete injection system at Burns Harbor was $15,073,106 (1990$) for the 7,200 NTHM/day blast furnace.
- The total fixed costs (labor and repair costs) at Burns Harbor were $6.25/ton of coal. The total variable costs (water, electricity, natural gas, and nitrogen) were $3.56/ton of coal. Coal costs were $50-60/ton.
- At a total cost of $60/ton and a natural gas cost of $2.85/10$^6$ Btu, the iron cost savings would be about $6.50/ton of iron produced.
- Based on the Burns Harbor production of 5.2 million tons of iron per year, the annual savings is about $34 million/yr.

## Project Summary

Two high-capacity blast furnaces, Units C and D at Bethlehem Steel's Burns Harbor Plant, were retrofitted with BFGCI technology. Each unit has a production capacity of 7,000 NTHM/day. The two units use about 2,800 tons/day of coal during full operation. This project represents the first U.S. blast furnace designed to deliver granular (coarse) coal. All previous blast furnaces have been designed to deliver pulverized (fine) coal. The project also represents about a 100% scale-up from CPC-Macawber's Scunthorpe Works in England where the technology was developed.

In addition to testing the technology on large, high-production blast furnaces, Bethlehem Steel conducted testing on different types of U.S. coal to determine the effect on blast furnace performance. Tests included eastern bituminous coals with sulfur contents of 0.8–2.8% and western subbituminous coals having 0.4–0.9% sulfur. Specifically, the objective of the test program was to determine the effect of coal grind and coal type on blast furnace performance. Other trials include determining the effects of coal types and coal chemistry on furnace performance. To date, results of two trials have been reported—a base period using low-ash, low-volatile coal and a trial period using high-ash, low-volatile coal.

### Operational Summary

Virginia Pocahantas and Buchanan, a chemically similar coal from the same seam, but from a different mine, were used all of 1996. During the entire month of October 1996, the Burns Harbor C blast furnace operated without interruption using Virginia Pocahantas. This low-ash, low-volatile, high-carbon coal provided a high coke replacement value for the base period test. The coal feed rate varied from 246–278 lb/NTHM on a daily basis for an average feed rate of 264 lb/NTHM. The furnace coke rate during the period averaged 661 lb/NTHM. The granular coal injected in C furnace was about 15% minus 200 mesh for the month.

The injected coal rate of 264 lb/NTHM is one of the highest achieved since startup of the coal facility. Reliability of the coal system enabled the operators to reduce furnace coke to a low rate of 661 lb/NTHM. This low coke rate is not only economically beneficial, it is an indicator of the efficiency of furnace operation with regard to displacing coke with injected coal.

Hot metal chemistry, particularly silicon and sulfur content, is an important iron making parameter. Specific silicon and sulfur values with low variability are vital to meeting steel-making specifications. The average values and standard deviations for silicon and sulfur can be seen in Exhibit 5-43. These values are compared to typical operation data on natural gas collected in January 1995.

Exhibit 5-43 also shows the significant operating changes that occur with the use of injected coal versus natural gas. The wind volume on the furnace decreased significantly with the use of coal. Oxygen enrichment increased from 24.4% to 27.3% with coal. The amount of moisture added to the furnace in the form of steam significantly increased from 3.7 grains/SCF to 19.8 grains/SCF. All of these variables were increased by operating personnel to maintain adequate burden material movement. These actions also increased the permeability of the furnace burden column, which is a function of the blast rate and the pressure drop through the furnace. The larger the permeability value, the better the furnace burden movement and the better the reducing gas flow rate through the furnace column. During the base period, the permeability indicated overall acceptable operation using low-ash, low-volatile, high-carbon coal.

The next series of tests involved using a higher ash coal. In order to ensure that other variables did not influence the test results, Buchanan coal was used, but the ash content was increased by eliminating one of the usual coal cleaning steps. The ash content of the coal used for the high-ash trial was 7.70% compared to 5.30% for the base period trial and the 4.72% for the period immediately prior to the high-ash coal trial. As during the base trial period, the granular coal was about 15% minus 200 mesh. To ensure comparable results, Bethlehem Steel operators maintained consistent operation with the base period trials. A comparison of the high-ash trial to the base period is also contained in Exhibit 5-43. The amount of injected coal, general blast conditions, wind volume, blast pressure, top pressure, and moisture additions were comparable during the two trials.

The primary change in operation, as expected, was the increase in the blast furnace slag volume. With the higher ash coal, the 461 lb/NTHM slag volume was 8.7% higher than the baseline period of 424 lb/NTHM. The general conclusion is that higher ash content in the injected coal can be adjusted by the furnace operators and does not adversely affect overall furnace operations. However, the results lead to the conclusion that a 2.4 percentage point increase in injected coal ash results in a 8 lb/NTHM increase in the furnace coke rate after correcting for other variables. This is the amount of coke carbon needed to replace the lower carbon in the higher-ash coal without an additional process penalty.

### Environmental Summary

The greatest environmental benefit to the BFGCI is displacement of coke in favor of coal. Coke is essentially replaced on a pound-for-pound basis with granulated coal, up to 40% of the total requirements. The BFGCI technology has the potential to reduce pollutant emissions because coke production results in significant emissions of air toxics.

### Economic Summary

Capital cost for one complete injection system at Burners Harbor was approximately $15 million (1990$). This does not include infrastructure improvements, which cost $87 million at Burns Harbor. The fixed operating costs, which includes labor and repair costs, were $6.25/ton of coal. The variable operating costs, which include water, electricity, natural gas, and nitrogen, were $3.56/ton of

**Exhibit 5-43**
**BFGCI Test Results**

| | Pre-Demonstration January 1995 | Base October 1996 | High Ash Test May 28 – June 23, 1997 |
|---|---|---|---|
| **Production, NTHM/day delays** | **7,436** | **6,943** | **7,437** |
| **Coke Rate, lbs/NTHM Rep.** | 740 | 661 | 674 |
| **Natural Gas Rate, lbs/NTHM** | 141 | 0 | 5.0 |
| **Injected Coal Rate, lbs/NTHM** | 0 | 264 | 262 |
| **Total Fuel Rate, lbs/NTHM** | 881 | 925 | 940 |
| **Blast Conditions:** | | | |
| Dry Air, SCFM | 167,381 | 137,005 | 135,370 |
| Blast Pressure, psig | 38.9 | 38.8 | 38.3 |
| Permeability | 1.57 | 1.19 | 1.23 |
| Oxygen in wind, % | 24.4 | 27.3 | 28.6 |
| Temp, F | 2,067 | 2,067 | 2,012 |
| Moisture, grains/SCF | 3.7 | 19.8 | 20.7 |
| **Coke:** | | | |
| $H_2O$, % | 4.8 | 5.0 | 5.0 |
| **Hot Metal %:** | | | |
| Silicon (Standard Dev.) | 0.44 (.091) | 0.50 (.128) | 0.49 (0.97) |
| Sulfur (Standard Dev.) | 0.043 (.012) | 0.040 (.014) | 0.035 (.012) |
| Phos. | 0.070 | 0.072 | 0.073 |
| Mn. | 0.40 | 0.43 | 0.46 |
| Temp. F | 2,745 | 2,734 | 2,733 |
| **Slag %:** | | | |
| $SiO_2$ | 38.02 | 36.54 | 36.21 |
| $Al_2O_3$ | 8.82 | 9.63 | 9.91 |
| CaO | 37.28 | 39.03 | 39.40 |
| MgO | 12.02 | 11.62 | 11.32 |
| Mn | 0.45 | 0.46 | 0.45 |
| Sulfur | 0.85 | 1.39 | 1.40 |
| B/A | 1.05 | 1.10 | 1.10 |
| B/S | 1.30 | 1.39 | 1.40 |
| Volume, lbs/NTHM | 394 | 424 | 461 |

coal. Coal costs were $50–60/ton. This brought the total operating costs to $59.81–69.81/ton of coal. Using $60/ton of coal and a natural gas cost of $.88/10$^6$ Btu, the cost savings would be about $6.50/ton of iron produced. At Burns Harbor, which produces 5.2 million tons of iron per year, the savings would be about $34 million/yr. At Burners Harbor, the payback period is 3.44 years using a simple rate of return calculation.

## Commercial Applications

BFGCI technology can be applied to essentially all U.S. blast furnaces. The technology should be applicable to any rank coal commercially available in the U.S. that has a moisture content no higher than 10%. The environmental impacts of commercial application are primarily indirect and consist of a significant reduction of emissions resulting from diminished coke-making requirements. The BFGCI technology was developed jointly by British Steel and Simon-Macawber (now CPC-Macawber). British Steel has granted exclusive rights to market BFGCI technology worldwide to CPC-Macawber. CPC-Macawber also has the right to sublicense BFGCI rights to other organizations throughout the world. CPC-Macawber has also recently installed a similar facility at United States Steel Corporation's Fairfield blast furnace.

## Contacts

Robert Bouman, (610) 694-6792
Bethlehem Steel Corporation
Building C, Room 211
Homer Research Laboratory
Mountain Top Campus
Bethlehem, PA 18016
(610) 694-2981 (fax)
Douglas Archer, DOE/HQ, (301) 903-9443
Leo E. Makovsky, NETL, (412) 386-5814

## References

Hill, D.G. *et al.* "Blast Furnace Granular-Coal Injection System Demonstration Project." *Sixth Clean Coal Conference Proceedings: Volume II* - Technical Papers. April-May, 1998.

# Advanced Cyclone Combustor with Internal Sulfur, Nitrogen, and Ash Control

***Project completed.***

### Participant
Coal Tech Corporation

### Additional Team Members
Commonwealth of Pennsylvania, Energy Development Authority—cofunder

Pennsylvania Power and Light Company—supplier of test coals

Tampella Power Corporation—host

### Location
Williamsport, Lycoming County, PA (Tampella Power Corporation's boiler manufacturing plant)

### Technology
Coal Tech's advanced, air-cooled, slagging combustor

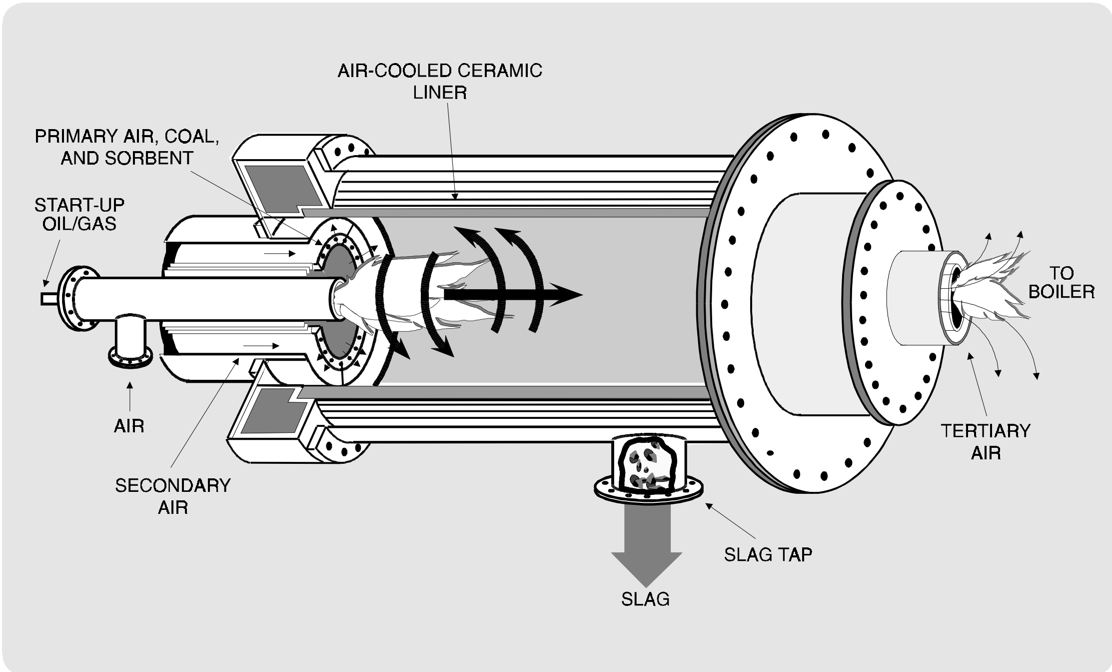
### Plant Capacity/Production
23 x $10^6$ Btu/hr of steam

### Coal
Pennsylvania bituminous, 1.0–3.3% sulfur

### Project Funding

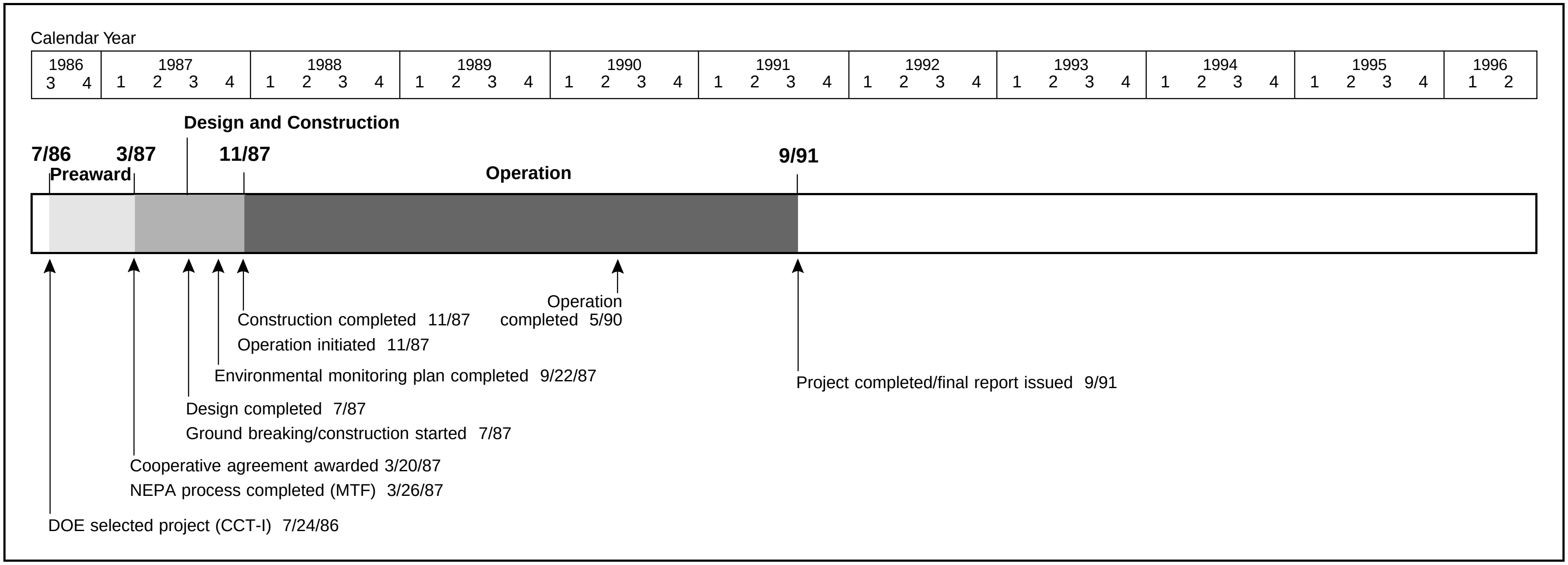
| | | |
|---|---|---|
| Total project cost | $984,394 | 100% |
| DOE | 490,149 | 50 |
| Participant | 494,245 | 50 |

### Project Objective
To demonstrate that an advanced cyclone combustor can be retrofitted to an industrial boiler and that it can simultaneously remove up to 90% of the $SO_2$ and 90–95% of the ash within the combustor and reduce $NO_x$ to 100 ppm.




### Technology/Project Description
Coal Tech's horizontal cyclone combustor is internally lined with an air-cooled ceramic. Pulverized coal, air, and sorbent are injected tangentially toward the wall through tubes in the annular region of the combustor to cause cyclonic action. In this manner, coal-particle combustion takes place in a swirling flame in a region favorable to particle retention in the combustor. Secondary air is used to adjust the overall combustor stoichiometry. Tertiary air is injected at the combustor/boiler interface. The ceramic liner is cooled by the secondary air and maintained at a temperature high enough to keep the slag in a liquid, free-flowing state. The secondary air is preheated by the combustor walls to attain efficient combustion of the coal particles in the fuel-rich combustor. Fine coal pulverization allows combustion of most of the coal particles near the cyclone wall. The combustor was designed to retain a high percentage of the ash and sorbent fed to the combustor as slag. For $NO_x$ control, the combustor is operated fuel rich, with final combustion taking place in the boiler furnace to which the combustor is attached. $SO_2$ is captured by injection of limestone into the combustor. The cyclonic action inside the combustor forces the coal ash and sorbent to the walls where it can be collected as liquid slag. Under optimum operating conditions, the slag contains a significant fraction of vitrified coal sulfur. Downstream sorbent injection into the boiler provides additional sulfur removal capacity.

In Coal Tech's demonstration, an advanced, air-cooled cyclone coal combustor was retrofitted to a 23 x $10^6$ Btu/hr, oil-designed package boiler located at the Tampella Power Corporation boiler factory in Williamsport, Pennsylvania.




## Results Summary

### Environmental

- $SO_2$ removal efficiencies of over 80% were achieved with sorbent injection in the furnace at various calcium-to-sulfur (Ca/S) molar ratios.
- $SO_2$ removal efficiencies up to 58% were achieved with sorbent injection in the combustor at a Ca/S molar ratio of 2.0.
- A maximum of one-third of the coal's sulfur was retained in the dry ash removed from the combustor (as slag) and furnace hearth.
- At most, 11% of the coal's sulfur was retained in the slag rejected through the combustor's slag tap.
- $NO_x$ emissions were reduced to 184 ppm by the combustor and furnace, and to 160 ppm with the addition of a wet particulate scrubber.
- Combustor slag was essentially inert.
- Ash/sorbent retention in the combustor as slag averaged 72% and ranged from 55–90%. Under more fuel- lean conditions, retention averaged 80%.
- Meeting local particulate emissions standards required the addition of a wet venturi scrubber.

### Operational

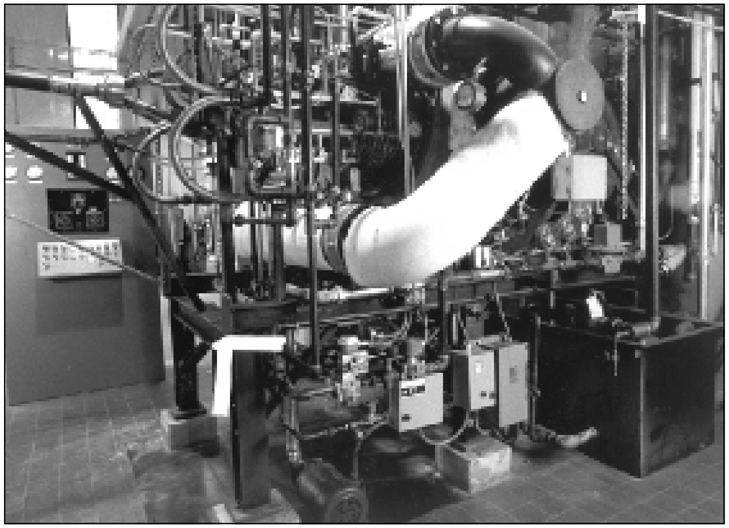
- Combustion efficiencies of over 99% were achieved.
- A 3-to-1 combustor turndown capability was demonstrated. Protection of combustor refractory with slag was shown to be possible.
- A computer-controlled system for automatic combustor operation was developed and demonstrated.

### Economic

- Because the technology failed to meet commercialization criteria, economics were not developed during the demonstration. However, subsequent efforts indicate that incremental capital costs for installing the coal combustor in lieu of oil or gas systems are \$100–200/kW.

## Project Summary

The novel features of Coal Tech's patented ceramic-lined, slagging cyclone combustor included its air-cooled walls and environmental control of $NO_x$, $SO_2$, and solid waste emissions. Air cooling took place in a very compact combustor, which could be retrofitted to a wide range of industrial and utility boiler designs without disturbing the boiler's water-steam circuit. In this technology, $NO_x$ reduction was achieved by staged combustion, and $SO_2$ was captured by injection of limestone into the combustor and/or boiler. Critical to combustor performance was removal of ash as slag, which would otherwise erode boiler tubes. This was particularly important in oil furnace retrofits where tube spacing is tight (made possible by the low-ash content of oil-based fuels).



▲ The slagging combustor, associated piping, and control panel for Coal Tech's advanced ceramic-lined slagging combustor are shown.

The test effort consisted of 800 hours of operation, including five individual tests, each of four days, duration. An additional 100 hours of testing was performed as part of a separate ash vitrification test. Test results obtained during operation of the combustor indicated that Coal Tech attained most of the objectives contained in the cooperative agreement. About eight different Pennsylvania bituminous coals with sulfur contents ranging from 1.0–3.3% and volatile matter contents ranging from 19–37% were tested.

### Environmental Performance

A maximum of over 80% $SO_2$ reduction measured at the boiler outlet stack was achieved using sorbent injection in the furnace at various Ca/S molar ratios. A maximum $SO_2$ reduction of 58% was measured at the stack with limestone injection into the combustor at a Ca/S molar ratio of 2. A maximum of one-third of the coal's sulfur was retained in the dry ash removed from the combustor and furnace hearths, and as much as 11% of the coal's sulfur was retained in the slag rejected through the slag tap. Additional sulfur retention in the slag is possible by increasing the slag flow rate and further improving fuel-rich combustion and sorbent-gas mixing.

With fuel-rich operation of the combustor, a three-fourths reduction in measured boiler outlet stack $NO_x$ was obtained, corresponding to 184 ppm. An additional 5–10% reduction was obtained by the action of the wet particulate scrubber, resulting in atmospheric $NO_x$ emissions as low as 160 ppm.

All the slag removed from the combustor produced trace metal leachates well below EPA's Drinking Water Standard.

Total ash/sorbent retention as slag in the combustor, under efficient combustion operating conditions, averaged 72% and ranged from 55–90%. Under more fuel-lean conditions, the slag retention averaged 80%. In post-CCT project, tests on flyash vitrification in the combustor, modifications to the solids injection system, and increases in the slag flow rate produced substantial increases in the slag retention rate. To meet local stack particulate emission standards, a wet venturi particulate scrubber was installed at the boiler outlet.

### Operational Performance

Combustion efficiencies exceeded 99% after proper operating procedures were achieved. Combustor turndown to 6 x $10^6$ Btu/hr from a peak of 19 x $10^6$ Btu/hr (or a 3-to-1 turndown) was achieved. The maximum heat input during the tests was around 20 x $10^6$ Btu/hr, even though the combustor was designed for 30 x $10^6$ Btu/hr and the boiler was thermally rated at around 25 x $10^6$ Btu/hr. This situation resulted from facility limits on water availability for the boiler. In fact, due to the lack of sufficient water cooling, even 20 x $10^6$ Btu/hr was borderline, so that most of the testing was conducted at lower rates.

Different sections of the combustor had different materials requirements. Suitable materials for each section were identified. Also, the test effort showed that operational procedures were closely coupled with materials durability. As an example, by implementing certain procedures, such as changing the combustor wall temperature, it was possible to replenish the combustor refractory wall thickness with slag produced during combustion rather than by adding ceramic to the combustor walls.

The combustor's total operating time during the life of the CCT project was about 900 hours. This included approximately 100 hours of operation in two other flyash vitrification tests projects. Of the total time, about one-third was with coal; about 125 tons of coal were consumed.

Developing proper combustor operating procedures was also a project objective. Not only were procedures for properly operating an air-cooled combustor developed, but the entire operating database was incorporated into a computer-controlled system for automatic combustor operation.

### Commercial Applications

In conclusion, the goal of this project was to validate the performance of the air-cooled combustor at a commercial scale. While the combustor was not yet fully ready for sale with commercial guarantees, it was believed to have commercial potential.  Subsequent work was undertaken, which has brought the technology close to commercial introduction.

### Contacts

Bert Zauderer, President, (610) 667-0442
Coal Tech Corporation
P.O. Box 154
Merion Station, PA 19066
coaltechbz@compuserve.com
William E. Fernald, DOE/HQ, (301) 903-9448
James U. Watts, NETL, (412) 386-5991

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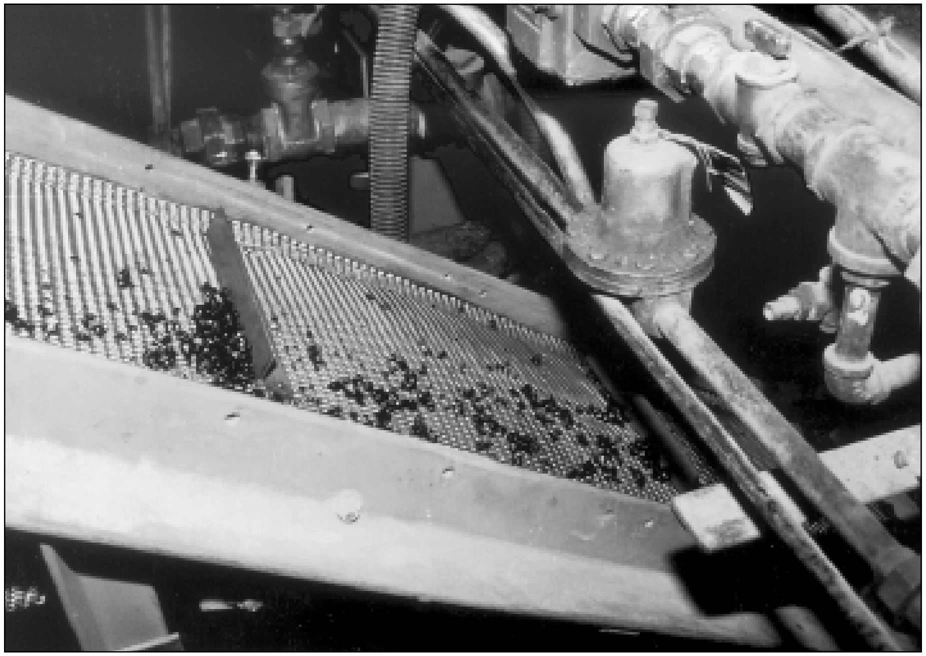


▲ Coal Tech's slagging combustor demonstrated the capability to retain, as slag, a high percentage of the non-fuel components injected into the combustor.  The slag, shown on the conveyor, is essentially an inert, glassy by-product with value in the construction industry as an aggregate or in the manufacture of abrasives.

# Cement Kiln Flue Gas Recovery Scrubber

***Project completed.***

### Participant
Passamaquoddy Tribe

### Additional Team Members
Dragon Products Company—project manager and host
HPD, Incorporated—designer and fabricator of tanks and heat exchanger
Cianbro Corporation—constructor

### Location
Thomaston, Knox County, ME (Dragon Products Company's coal-fired cement kiln)

### Technology
Passamaquoddy Technology Recovery Scrubber™

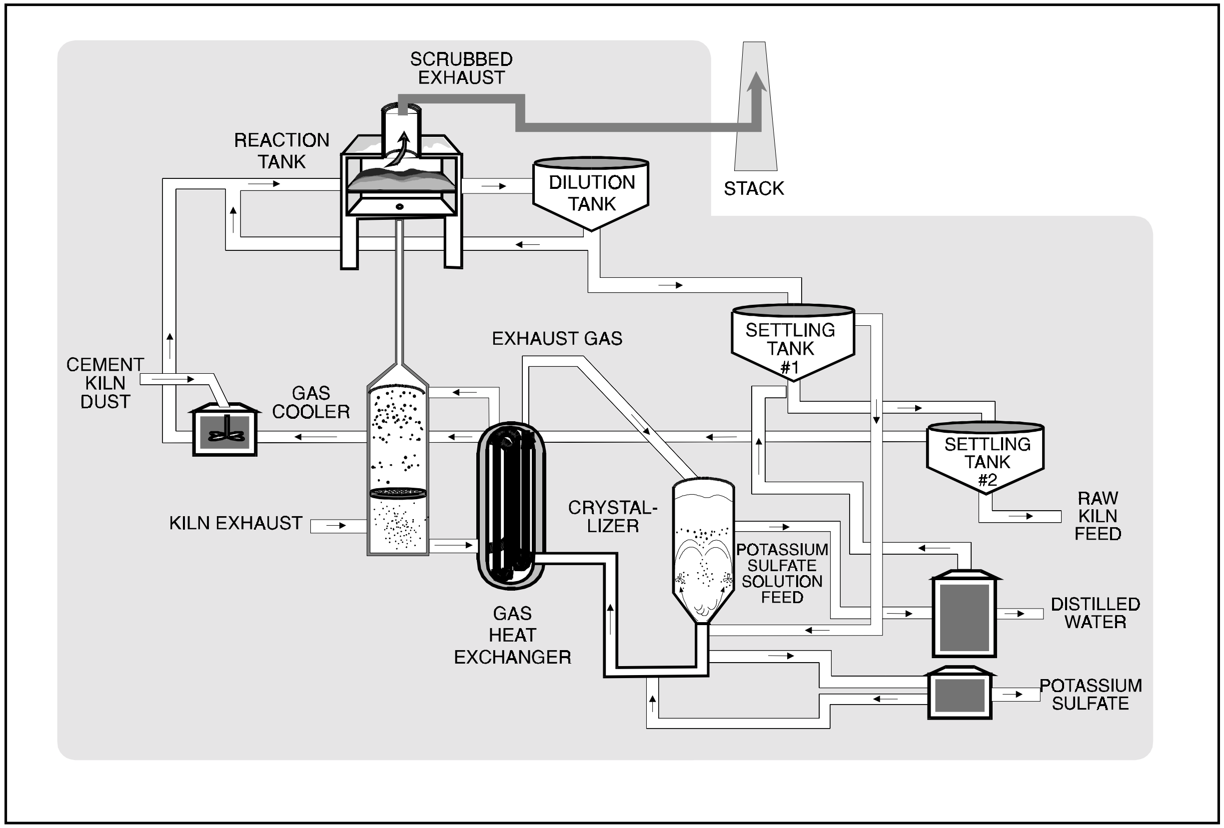
### Plant Capacity/Production
1,450 tons/day of cement; 250,000 scfm of kiln gas; and up to 274 tons/day of coal

### Coal
Pennsylvania bituminous, 2.5–3.0% sulfur

### Project Funding

| | | |
|---|---|---|
| Total project cost | $17,800,000 | 100% |
| DOE | 5,982,592 | 34 |
| Participant | 11,817,408 | 66 |

### Project Objective
To retrofit and demonstrate a full-scale industrial scrubber and waste recovery system for a coal-burning wet process cement kiln using waste dust as the reagent to accomplish 90–95% $SO_2$ reduction using high-sulfur eastern coals; and to produce a commercial by-product, potassium-based fertilizer by-products.




### Technology/Project Description
The Passamaquoddy Technology Recovery Scrubber™ uses cement kiln dust (CKD), an alkaline-rich (potassium) waste, to react with the acidic flue gas. This CKD, representing about 10% of the cement feedstock otherwise lost as waste, is formed into a water-based slurry and mixed with the flue gas as the slurry passes over a perforated tray that enables the flue gas to percolate through the slurry. The $SO_2$ in the flue gas reacts with the potassium to form potassium sulfate, which stays in solution and remains in the liquid as the slurry undergoes separation into liquid and solid fractions. The solid fraction, in thickened slurry form and freed of the potassium and other alkali constituents, is returned to the kiln as feedstock (it is the alkali content that makes the CKD unusable as feedstock). No dewatering is necessary for the wet process used at the Dragon Products Plant. The liquid fraction is passed to a crystallizer that uses waste heat in the flue gas to evaporate the water and recover dissolved alkali metal salts. A recuperator lowers the incoming flue gas temperature to prevent slurry evaporation, enables the use of low-cost fiberglass construction material, and provides much of the process water through condensation of exhaust gas moisture.

The Passamaquoddy Technology Recovery Scrubber™ was constructed at the Dragon Products Company's cement plant in Thomaston, Maine, a plant that can process approximately 450,000 tons/yr of cement. The process was developed by the Passamaquoddy Indian Tribe while it was seeking ways to solve landfill problems, which resulted from the need to dispose of CKD from the cement-making process.

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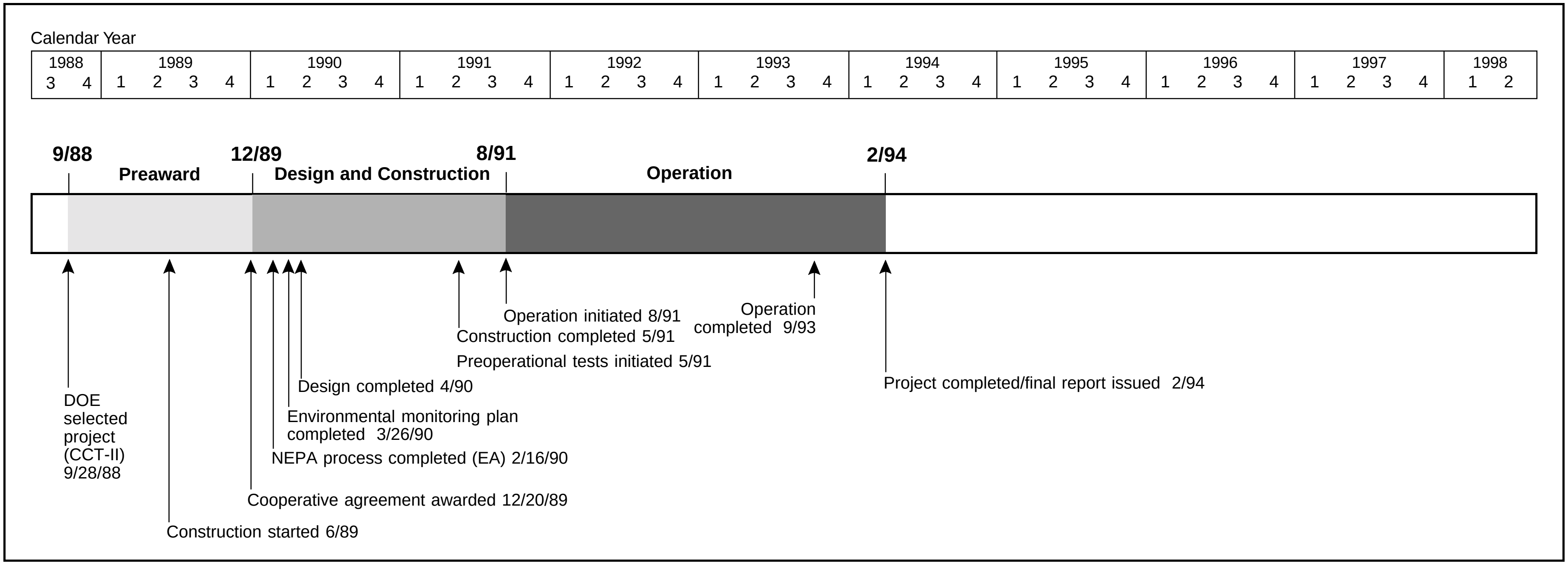
Passamaquoddy Technology Recovery Scrubber is a trademark of the Passamaquoddy Tribe.




## Results Summary

### Environmental

- The $SO_2$ removal efficiency averaged 94.6% during the last several months of operation and 89.2% for the entire operating period.
- The $NO_x$ removal efficiency averaged nearly 25% during the last several months of operation and 18.8% for the entire operating period.
- All of the 250 ton/day CKD waste produced by the plant was renovated and reused as feedstock, which resulted in reducing the raw feedstock requirement by 10% and eliminating solid waste disposal costs.
- Particulate emission rates of 0.005–0.007 gr/scf, about one-tenth that allowed for cement kilns, were achieved with dust loadings of approximately 0.04 gr/scf.
- Pilot testing conducted at U.S. Environmental Protection Agency laboratories under Passamaquoddy Technology, L.P. sponsorship showed 98% HCl removal.
- On three different runs, VOC (as represented by alpha-pinene) removal efficiencies of 72.3, 83.1, and 74.5% were achieved.
- A reduction of approximately 2% in $CO_2$ emissions was realized through recycling of the CKD.

### Operational

- During the last operating interval, April to September 1993, recovery scrubber availability (discounting host site downtime) steadily increased from 65% in April 1993 to 99.5% in July 1993.

### Economic

- Capital costs are approximately $10,090,000 (1990$) for a recovery scrubber to control emissions from a 450,000-ton/yr wet process plant, with a simple payback estimated in 3.1 years.
- Operating and maintenance costs, estimated at $500,000/yr, plus capital and interest costs, are generally offset by avoided costs associated with fuel, feedstock, and waste disposal and with revenues from the sale of fertilizer.

## Project Summary

The Passamaquoddy Technology Recovery Scrubber™ is a unique process that achieves efficient acid gas and particulate control through effective contact between flue gas and a potassium-rich slurry composed of waste kiln dust. Flue gas passes through the slurry as it moves over a special sieve tray. This results in high $SO_2$ and particulate capture, some $NO_x$ reduction, and sufficient uptake of the potassium (an unwanted constituent in cement) to allow the slurry to be recycled as feedstock. Waste cement kiln dust, exhaust gases (including waste heat), and wastewater are the only inputs to the process. Renovated cement kiln dust, potassium-based fertilizer, scrubbed exhaust gas, and distilled water are the only proven outputs. There is no waste.

The scrubber was evaluated over three basic operating intervals dictated by winter shutdowns for maintenance and inventory and 14 separate operating periods (within these basic intervals) largely determined by unforeseen host-plant maintenance and repairs and a depressed cement market. Over the period August 1991 to September 1993, more than 5,300 hours was logged, 1,400 hours in the first operating interval, 1,300 hours in the second interval, and 2,600 hours in the third interval. Sulfur loadings varied significantly over the operating periods due to variations in feedstock and operating conditions.

### Operational Performance

Several design problems were discovered and corrected during startup. No further problems were experienced in these areas during actual operation.

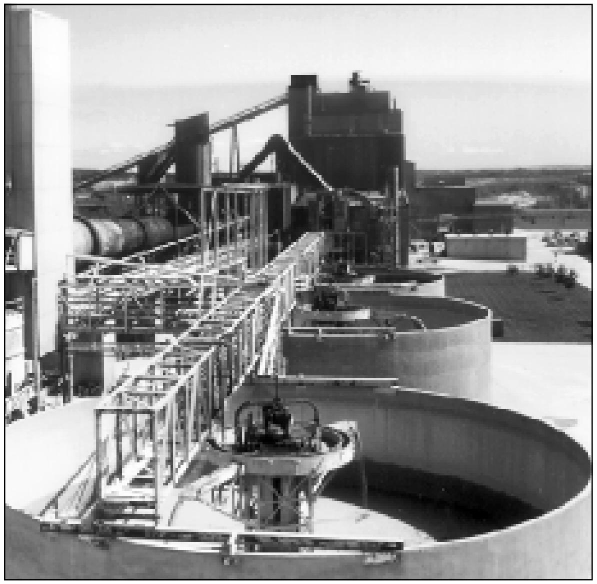
Two problems persisted into the demonstration period. The mesh-type mist eliminator, which was installed to prevent slurry entrainment in the flue gas, experienced plugging. Attempts to design a more efficient water spray for cleaning failed. However, replacement with a chevron-type mist eliminator prior to the third operating interval was effective. Potassium sulfate pelletization proved to be a more difficult problem. The cause was eventually isolated and found to be excessive water entrainment due to carry-over of gypsum and syngenite. Hydroclones were installed in the crystallizer circuit to separate the very fine gypsum and syngenite crystals from the much coarser potassium sulfate crystals. Although the correction was made, it was not completed in time to realize pellet production during the demonstration period. After all modifications were completed, the recovery scrubber entered into the third and final operating interval—April to September 1993. During this interval, recovery scrubber availability (discounting host site downtime) steadily increased from 65% in April to 99.5% in July.

### Environmental Performance

An average 250 tons/day of CKD waste generated by the Dragon Products plant was used as the sole reagent in the recovery scrubber to treat approximately 250,000 scfm of flue gas. All the CKD, or approximately 10 tons/hr, were renovated and returned to the plant as feedstock and mixed with about 90 tons/hr of fresh feed to make up the required 100 tons/hr. The alkali in the CKD was converted to potassium-based fertilizer, eliminating all solid waste. Exhibit 5-44 lists the number of hours per operating period, $SO_2$ and $NO_x$ inlet and outlet readings in pounds per hour, and removal efficiency as a percentage for each operating period.

**Exhibit 5-44**
**Summary of Emissions and Removal Efficiencies**

| Operating Period | Operating Time (hr) | Inlet (lb/hr) $SO_2$ | Inlet (lb/hr) $NO_x$ | Outlet (lb/hr) $SO_2$ | Outlet (lb/hr) $NO_x$ | Removal Efficiency (%) $SO_2$ | Removal Efficiency (%) $NO_x$ |
|---|---|---|---|---|---|---|---|
| 1 | 211 | 73 | 320 | 10 | 279 | 87.0 | 12.8 |
| 2 | 476 | 71 | 284 | 11 | 260 | 84.6 | 08.6 |
| 3 | 464 | 87 | 292 | 13 | 251 | 85.4 | 14.0 |
| 4 | 259 | 131 | 252 | 16 | 165 | 87.6 | 34.5 |
| 5 | 304 | 245 | 293 | 28 | 243 | 88.7 | 17.1 |
| 6 | 379 | 222 | 265 | 28 | 208 | 87.4 | 21.3 |
| 7 | 328 | 281 | 345 | 28 | 244 | 90.1 | 29.3 |
| 8 | 301 | 124 | 278 | 10 | 188 | 91.8 | 32.4 |
| 9 | 314 | 47 | 240 | 7 | 194 | 85.7 | 19.0 |
| 10 | 402 | 41 | 244 | 6 | 218 | 86.1 | 10.5 |
| 11 | 460 | 36 | 315 | 6 | 267 | 83.4 | 15.0 |
| 12 | 549 | 57 | 333 | 2 | 291 | 95.9 | 12.4 |
| 13 | 464 | 86 | 288 | 4 | 223 | 95.0 | 22.6 |
| 14 | 405 | 124 | 274 | 9 | 199 | 92.4 | 27.4 |
| Total operating time | 5,316 | | | | | | |
| **Weighted Average** | | **109** | **289** | **12** | **234** | **89.2** | **18.8** |



▲ The Passamaquoddy Technology Recovery Scrubber™ was successfully demonstrated at Dragon Products Company's cement plant in Thomaston, Maine.

Average removal efficiencies during the demonstration period were 89.2% for $SO_2$ and 18.8% for $NO_x$ emissions. No definitive explanation for the $NO_x$ control mechanics was available at the conclusion of the demonstration.

Aside from the operating period emissions data, an assessment was made of inlet $SO_2$ load impact on removal efficiency. For $SO_2$ inlet loads in the range of 100 lb/hr or less, recovery scrubber removal efficiency averaged 82.0%. For $SO_2$ inlet loads in the range of 100–200 lb/hr, removal efficiency increased to 94.1% and up to 98.5% for loads greater than 200 lb/hr.

In compliance testing for Maine's Department of Environmental Quality, the recovery scrubber was subjected to dust loadings of approximately 0.04 gr/scf and demonstrated particulate emission rates of 0.005–0.007 gr/scf—less than one-tenth the current allowable limit.

## Economic Performance

The estimated "as-built" capital cost to reconstruct the Dragon Products prototype, absent the modifications, is $10,090,000 in 1990 dollars.

Annual operating and maintenance costs are estimated at $500,000. Long-term annual maintenance costs are estimated at $150,000. Power costs, estimated at $350,000/yr, are the only significant operating costs. There are no costs for reagents or disposal, and no dedicated staffing or maintenance equipment are required.

Considering various revenues and avoided costs that may be realized by installing a recovery scrubber similar in size to the one used at Dragon Products, simple payback on the investment is projected in as little as 3.1 years. In making this projection, $6,000,000 was added to the "as-built" capital costs to allow for contingency, design/permitting, construction interest, and licensing fees.

## Commercial Applications

Of the approximately 2,000 Portland cement kilns in the world, about 250 are in the United States and Canada. These 250 kilns emit an estimated 230,000 tons/yr of $SO_2$ (only three plants have $SO_2$ controls, one of which is the Passamaquoddy Technology Recovery Scrubber™). The applicable market for $SO_2$ control is estimated at 75% of the 250 installations. If full penetration of this estimated market were realized, approximately 150,000 tons/yr of $SO_2$ reduction could be achieved.

The scrubber became a permanent part of the cement plant at the end of the demonstration. A feasibility study has been completed for a Taiwanese cement plant.

## Contacts

Thomas N. Tureen, Project Manager, (207) 773-7166
Passamaquoddy Technology, L.P.
1 Monument Way
Portland, ME 04101
(207) 773-7166
(207) 773-8832 (fax)
William E. Fernald, DOE/HQ, (301) 903-9448
John C. McDowell, NETL, (412) 386-6175

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